Electrical Power System Health Management

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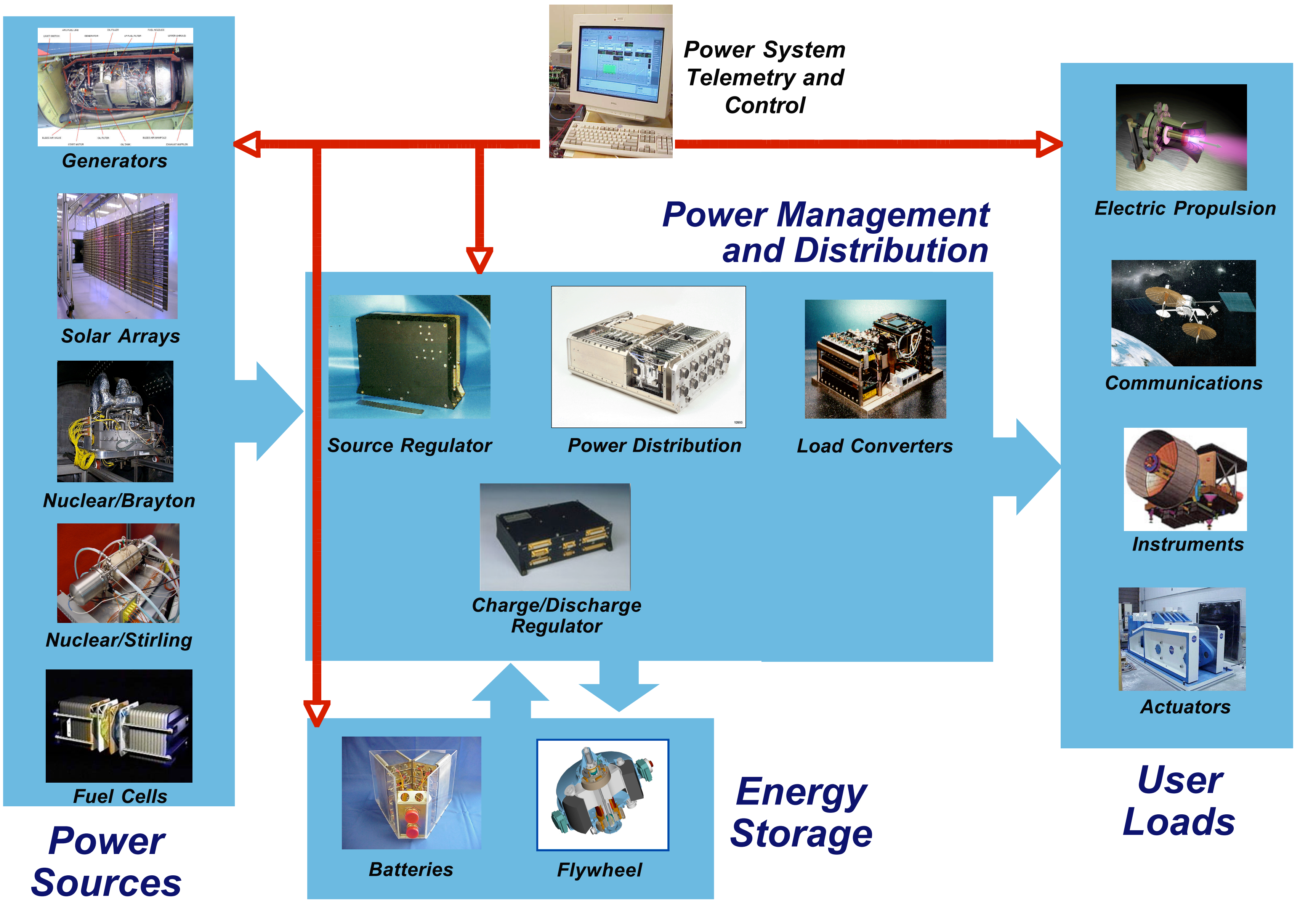
Overview

- Aerospace Electrical Power Systems
- Power System Failure Modes
  - Current HM practices
- Survey of Existing Power System HM
- Future Power System HM
- Conclusions

Aerospace Power System

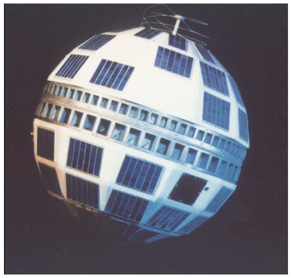


General Power System HM Observations

- Needs are mainly
  - Isolation and recovery from failure.
  - Managing component and system degradation.
- What can we do well today?
  - Isolate hard failures.
  - Recover using built-in redundancy.
  - Track and trend degradation of power sources.
- What would we like to be able to do?
  - Measure the health of power electronics, cables, and connectors to predict impeding failures.
  - Increase modularity to reduce redundancy penalties.
    - Sources, storage, and distribution
  - Detect incipient faults (arcing, leakage, cable faults).
  - Employ highly reconfigurable distribution architectures.

Fault Modes - Solar Arrays

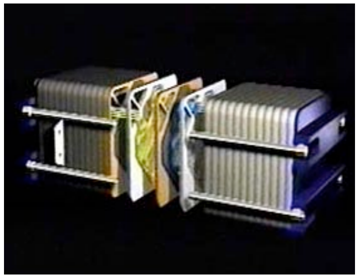
- Catastrophic failure not a concern for HM
  - Arrays are inherently modular and fault tolerant
    - Cell bypass and reverse-blocking diodes
  - Complete array failures are rare
- Accelerated degradation is the main concern
  - Radiation, contamination, cover glass clouding, arcing and sputtering of metals, dust accumulation.
- Current HM Techniques
  - Data trending to predict future power availability.
  - Mission planning and corrections are ground-based

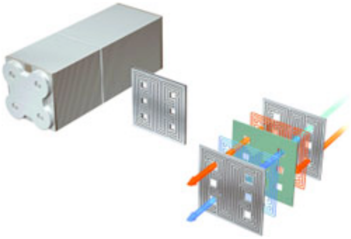


Failure/Degradatio n	Mechanisms	Detection	Diagnosis
Solar panel failure	Deployment failure, mechanical separation	Array current/voltage sensor, insolation sensor.	Zero current/voltage output with good insolation.
String failure	Micrometeoroid damage, cable failure, shadowing	String current/voltage sensor, insolation sensor	Zero string current/voltage output with good insolation.
Cell failure	Micrometeoroid damage, shadowing	String current/voltage sensor	Degraded string performance in relation to others.
Array pointing failure	Array drive lockup, loss of spacecraft attitude control	Sun sensor, array insolation sensor	Lower than expected array power, lack of sun tracking.
Array degradation	radiation damage, contaminates, cover glass clouding	Array current/voltage sensor, insolation sensor. IV curve test	Historical trend data showing reduced power at equivalent insolation.

Fault Modes - Fuel Cells

- Failures are the major concern
  - Most failures are non-correctable
  - Cell crossover - continued operation endangers vehicle & crew
  - Reactant flow - manifolds prevent partial isolation.
  - Cell flooding corrected using purge valves (if present)
- Current HM Techniques
  - Extensive instrumentation of ancillary components.
    - Temperature, pressure, flow meters
    - Used for hard-limit shutdown, some closed loop control
  - Relative health measured in cell voltage data.
  - Opportunity for interconnected, intelligent algorithms that could improve performance and safety.

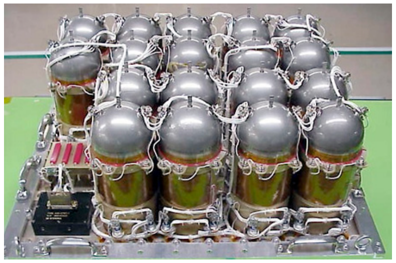


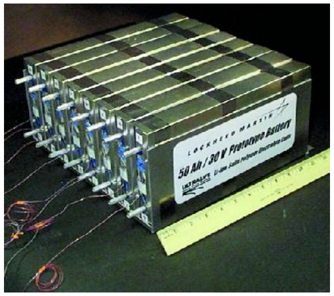


Failure/Degradatio n	Mechanisms	Detection	Diagnosis
Cell reactant crossover	Failure or leak of the reactant separator in a cell.	Cell voltage, stack temperature, and pressure.	Gradual loss of cell and/or stack voltage; rapid loss indicates complete cell failure.
Cell flooding	Excess water in cell blocks reaction sites.	Cell voltage, stack temperature, and pressure.	Gradual loss of cell and/or stack voltage.
Cell degradation	Changes to catalyst and membranes over time.	Cell voltage and stack temperature.	Degradation in cell and/or stack voltage over time. Weak cell affects entire stack.
Ancillary failures	Pressure regulator failure, line leaks, valve failure	Pressure and temperature sensors	Pressure and temperature hard-limits set by system design requirements.

Fault Modes - Batteries

- Failures easy to detect, generally non-recoverable
  - Multiple batteries used for reliability
  - Most failures to due single cell failure
    - Extensive screening program to eliminate poor cells
- Accelerated degradation is the primary concern
  - Charge/discharge profiles, temperature
  - Some chemistries benefit from “re-conditioning”
- Current HM Techniques - Ground-based
  - Significant cell telemetry
    - voltage, temperature, pressure
  - High quality amp-hour calculations





Failure/Degradatio n	Mechanisms	Detection	Diagnosis
Battery failure	Mechanical separation, catastrophic battery failure-rupture of battery housing (open), cable failure	Battery current sensor	Inability of battery to deliver current during discharge, inability of battery to accept capacity during charge
Cell failure (short)	Manufacturing defect, containment failure	Cell voltage sensor, Temperature sensor	Unexpectedly low cell voltage, Unusually high cell temperature
Cell failure (open)	Electrolyte vent, cell case rupture, cell drying out	Current sensor, voltage sensor	Loss of amp-hour or watt-hour capacity
Cell degradation	Electrochemical aging, temperature effects, increase in internal resistance	Cell voltage or half-battery voltage sensor	Cell or half-battery voltage out of family
Battery electronics failure (charge circuitry)	Overcharge of cell/battery, over-discharge of cell/battery	Cell/Battery current sensor, temperature-compensated voltage sensor, temperature-compensated pressure sensor	Cell/battery voltage too high or too low (beyond design limitations), insufficient capacity

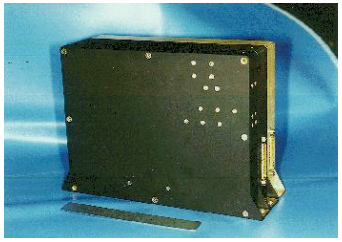
Fault Modes - Flywheel Energy Storage

- Catastrophic failure of the rotor is the major concern
  - De-rating and pre-failure detection key to prevention
- Other failures mitigated by reducing capacity
  - Magnetic bearings, thermal, vacuum, rotor growth
- Potential HM Techniques
  - Initiation of rotor cracks can be detected using the magnetic bearing performance and sensing.

Failure/Degradatio n	Mechanisms	Detection	Diagnosis
Rotor failure	Partial or Catastrophic mechanical failure	Magnetic bearing monitoring.	Sudden, extreme change in rotor balance detected in mag. bearing controls.
Magnetic bearing failure	Loss of drive power, coil failure, Sensor or controller failure.	Rotor position sensors	Disagreement between sensors and plant model observer
Motor/Generator	Coil failure open or shorted.	Current sensor, speed sensor	High or low currents detected, speed degradation when it should be increasing
Rotor degradation	Fatigue over time reduces tensile strength of the rotor. Creep (time and temperature effects).	Magnetic bearing monitoring.	Sudden changes in rotor balance can signify crack development and propogation.
Thermal	Externally heated, thermal control system failure	Infrared thermal detectors, stator thermocouples	Rotor temperature out of range.
Vacuum	Vacuum chamber leak, contamination by gases or dust	Infrared thermal detectors, watt-hour meters.	Unexpected rotor heating at high speeds, loss of roundtrip energy efficiency.
Power electronics and control	Mag bearing drive and control, motor drive inverter, generator active rectifier, digital controller	Current and voltage sensors	Loss of flywheel charge/discharge control.

Fault Modes - Power Regulation

- Generally intolerant to internal failures
  - Some topologies are more tolerant than others
  - Multiple units used for reliability
- Degradation difficult to detect
  - Thermal cycling and wear, stress events, radiation, etc.
  - Measurable changes may be miniscule.
  - Sudden failures without degradation are possible
- HM Techniques
  - Steady-state temperature, electrical measurements.
  - Digital control offers potential for large improvement



Failure/Degradation	Mechanisms	Detection	Diagnosis
Power converter loss of output power	Internal failure, commanded off, loss of input voltage	Input and output voltage, output current, on-off command sensor	Loss of output voltage with good input voltage, low currents, and verified on command.
Power converter loss of output regulation	Internal failure, input voltage out of range, load out of range.	Input and output voltage sensors, output current sensor	Output voltage out of expected regulation range.
Excessive power converter noise	Internal failure, passive filter failure, system instability.	High frequency Input voltage and current sensor	Output voltage out of expected regulation range.
Motor drive failure	Internal power electronics failure, motor load failure.	Voltage and current sensors	Loss of output current and/or output voltage.
Battery charger failure	Internal power electronics failure, sensor failure.	Battery current sensor	Battery charge current zero
Battery discharger failure	Internal power electronics failure, sensor failure.	Battery current sensor	Battery discharge current zero
Solar array regulator failure	Internal power electronics failure, sensor failure.	Array current sensor	Solar array current zero

Fault Modes - Power Distribution

- Hard failures
  - Switch failures - over use, exceeding limits, lifetime
  - Cable failures - short and open circuits.
- Soft failures
  - Shunt failures - arcing, leakage currents
  - Series failures - conduction degradation
- Failures require isolation and re-routing of power
- HM Techniques
  - Emerging capability in soft-fault and cable/connector degradation detection.

Failure/Degradation	Mechanisms	Detection	Diagnosis
Mechanical relay fails open	Coil/latch failure, contact failure	voltage sensor, aux. coil switch sensor	Coil activated but output voltage not equal to input voltage
Mechanical relay fails closed	Coil/latch failure, partial or full contact weld failure.	voltage sensor, aux. coil switch sensor	Cannot open relay and coil drive determined to be good.
Mechanical relay contact degradation	Contamination of contacts via outgassing of lubricants or repeated arcing and pitting during high current switching	Contact voltage sensor, current sensor	Increased voltage drop across the switch vs. current through the relay
Semiconductor switch fails open	High currents damage semiconductor or metal contacts.	voltage sensors (input, output, and gate drive)	Switch does not turn on (input voltage seen at the output) with a good gate drive signal
Semiconductor switch fails closed	High voltage “punch-through” damage of semiconductor. Radiation damage prevents turn-off	voltage sensors (input, output, and gate drive)	Switch does not turn off (output voltage goes to zero) with a low gate drive signal
Semiconductor gate drive degradation.	Radiation exposure lowers MOSFET threshold voltage. High temperature affects switch on resistance	voltage sensors (input, output, and gate drive), temperature sensors	Switch turns on with a low gate drive signal. Switch voltage drop higher than expected, high switch temperatures.
Cables/connectors open circuit	Mechanical damage/failure	Distributed voltage sensors	Voltage at one end of cable is vastly different than the other end.
Cables/connectors short circuit	Mechanical failure of the insulation. Mechanical cable failure.	Current sensor	Very high current detected at steady state (several milliseconds)
Cables/connector soft fault (arcing, leakage)	Mechanical failure of insulation.	High frequency current sensors. High accuracy current sensors.	Arcing detected by 2-5kHz noise in current sensor. Leakage detected by difference in current sensor at either ends of the cable.
Cables/connector degradation	Mechanical wear, environmental contamination	High accuracy voltage and current sensors	Increase in conduction loss detected using current and voltage sensors.

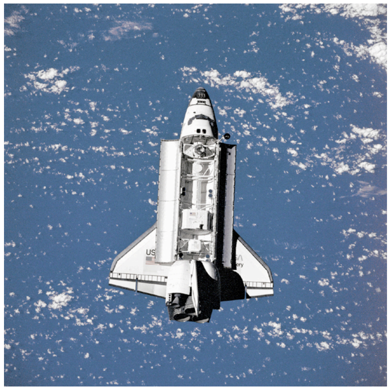
Survey of Power System HM

- Hubble Space Telescope
  - Extensive HM of Batteries and Solar Arrays
    - Continuously monitored by ground personnel
      - Battery energy storage capacity trending
      - Solar array power generation trending
    - All degradation within the expected range
    - Periodic reconditioning of batteries restores majority of capacity
  - HM techniques have extended the life in the face of delayed Shuttle repair missions.

- International Space Station
  - Ground-based, telemetry monitoring
  - NiH2 batteries
    - Cell temperature, voltage, pressure.
  - Solar arrays
    - String currents, voltage, panel temperature

HM in Current Power Systems

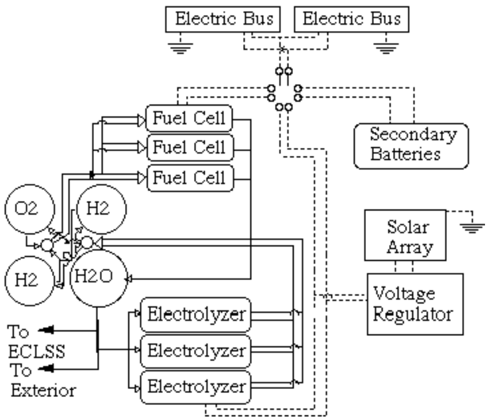
- Space Shuttle
  - HM prevalent in fuel cell system
    - Fuel cell is highly instrumented
    - Cryogenic reactant storage
  - Power Distribution System
    - Caution and warning monitoring
    - Ground telemetry monitoring of sensors



- Aeronautics
  - FDIR techniques applied to the engines
    - Main source of electrical power
  - Little HM used in power distribution system
    - Redundant hardware, scheduled maintenance
  - More electric aircraft (MEA) requires new developments in power system HM

Future of Power System HM

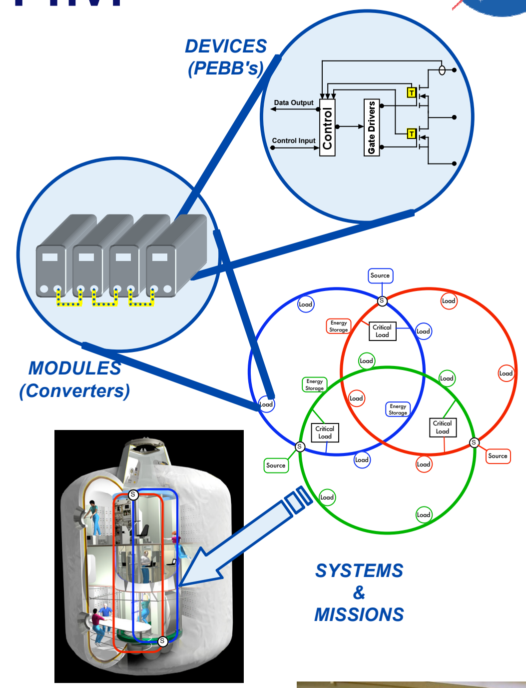
- Design Considerations
  - Plan Early in the Design Phase
    - Straightforward Approach with no Retrofitting
    - Support and Benefit Overall System Design
    - Impact Sensor Fidelity and Locations

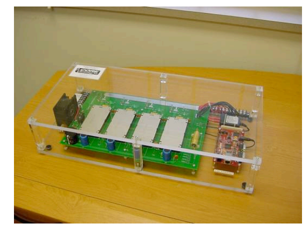


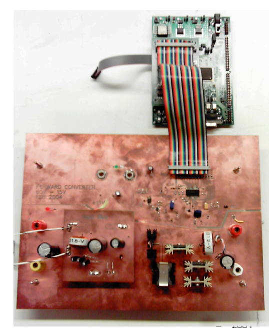
  - Development/Implementation Requirements
    - HM System Performance
    - Subsystem Interfaces
    - Processing Capabilities
  - Power Test Bed Environment
    - Permits Extensive Testing of HM System for V&V
    - Supports Simulation and HM Algorithm Development
    - Facilitates Testing of HM Component Hardware

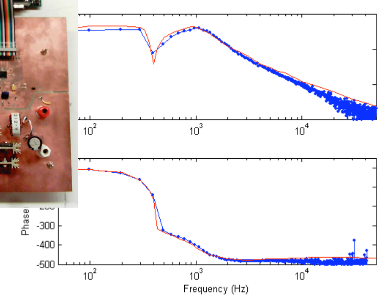
Future of Power System HM

- Hardware Advancements
  - Replace Redundant Components with highly Modular Components and Distribution Architectures
    - Mass and Cost Benefits
    - Minimize impact of single failures.
  - Digital Control of Power Electronics are Enabling
    - Sub-millisecond events require high bandwidth, local processors.
    - Signal processing for advanced fault detection (arcing).
  - Example: Modular Power Converters
    - Distributed, master-less control enables high level of modularity for increased reliability.
    - Advanced control algorithms improve performance and detect component degradations.
    - Capture and record anomalous events for overall health assessment and prognostics capabilities
  - Active Power and Stability Control
    - Vary Control Processes in Power Electronic Devices to Respond to Power System Changes



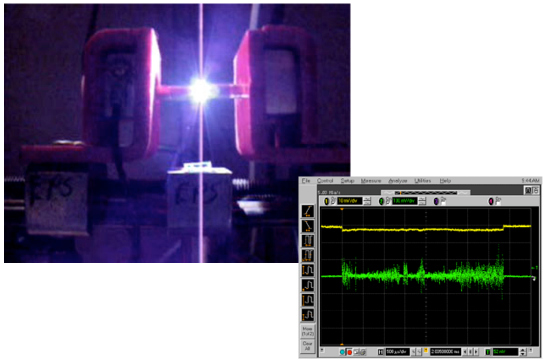


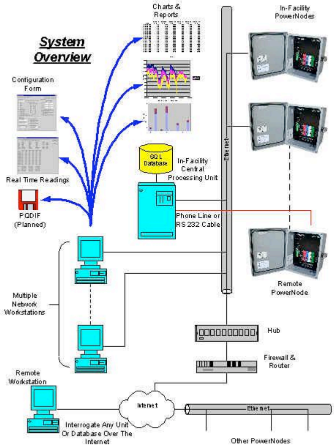




Future of Power System HM

- Intelligent Software
  - System-Level HM Functionality
    - Automated Fault Detection and Isolation
    - Recovery/Mission Planning
    - System Prognostics
  - Detect and Isolate “Hard” and “Soft” Faults
    - Source, Distribution Switch, and Load Converter Faults
    - Low-Level Arcing, Corona Discharge, Leakage, and Resistive Faults
  - On-Board Automation
    - Impractical Round-Trip Communication with Ground-Based Mission Controllers
    - System-Wide Energy Management
      - Ensure Overall Mission Success
      - Optimize Safety and Performance





Conclusions

- Aerospace Electrical Power Systems (EPS) are critical to mission success and safety.

- EPS failures and degradation
  - Mitigated by redundant hardware, dual-functionality, extra capacity
  - Ground-based data tracking, analysis and mission planning
  - Ground testing and scheduled maintenance

- Current HM techniques focus on energy sources.
  - Array, battery, fuel cell health and degradation prognostics
  - More work required to enable power management and distribution (PMAD) HM.

- Emerging technologies enable HM techniques applied to the entire EPS
  - Especially increased modularity and digital control